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WATER USE IN LCA

# Irrigation mix: how to include water sources when assessing freshwater consumption impacts associated to crops

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**Abstract**
*Purpose* Impacts of activities related to freshwater use are gaining interest among the life cycle assessment (LCA) community and several approaches are nowadays available in the literature. However, the general trend still is to ignore the assessment of its impact or, luckily, its inclusion on the inventory. This paper describes a procedure to incorporate water source information at the inventory level and evaluate the influence of that profile on the environmental impact assessment level.
*Methods* The methodology lies on two main elements: the "irrigation mix" concept and the freshwater ecosystem impact indicator already defined in the literature. By doing so, the results obtained can be easily integrated in LCA studies of irrigated crops, or more complex studies with agricultural ingredients, where only information regarding the amount (but not the origin) of irrigation water is available.
*Results and discussion* The results make more visible the benefits associated to the use of nonconventional, artificial water sources, by quantifying the improvement achieved on the water stress of a specific basin. Besides, the irrigation mix gives a better picture of the real contribution of irrigation to other impact categories (here, the global warming potential). Finally, the results were applied in a LCA study of lettuce production (an irrigated product cultivated in the studied region), and the method was analyzed against the criteria defined by the *International Reference Life Cycle Data System handbook*.
*Conclusions* The inclusion of the water mix in the inventory level (irrigation profile) as well as in the impact assessment level (water stress index) is straightforward to apply by LCA practitioners, resulting in a more realistic assessment of the impacts of freshwater consumption associated to crops. The implementation on a case study allowed the quantification of promoting alternative water sources in a region suffering from significant water stress as well as to improve knowledge on the environmental impact associated to freshwater consumed by one of the irrigated crops grown there. We recommend using the approach defined here in order to check its applicability to other river basins and products.

**Keywords** Blue water · Desalinated water · Impact assessment · Inventory · Life cycle assessment · Wastewater

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## 1 Introduction

Life cycle assessment (LCA) is recognized as a useful tool to assess the environmental burdens of products, processes, and services. In fact, during the last decades, its development and use has been fast and broad (Guinée et al. 2011). However, there are still some unresolved problems that require deeper research and consensus (Reap et al. 2008a,

b). One of them is related to the assessment of water use and consumption. Owens (2002) established a sound and clearly basis to include water balance in the life cycle inventory (LCI), which was later on further refined by Bayart et al. (2010). Despite the potential environmental consequences of freshwater quantity and quality loss on ecosystems and human health, the consideration of water in the life cycle impact assessment (LCIA) phase of an LCA study has been very limited until now (Berger and Finkbeiner 2010). The reason behind this is, probably, the complexity of the water resource characterized by different origins, diverse geographical distribution, and several ecosystems functions. In fact, from a global point of view, water, unlike oil, is a renewable resource; however, this does not mean that availability is unlimited. So, the water offered by rivers and aquifers in a certain period is limited to a certain amount and, therefore, their potential users (irrigation, domestic, and industrial purposes) can suffer from competition (Hoekstra et al. 2010).

Several approaches addressing water in the context of LCA have recently been published (e.g., Milà i Canals et al. 2009; Pfister et al. 2009). On the one hand, Milà i Canals et al. (2009) considered a midpoint perspective and described the method for evaluating the effects of direct water consumption on freshwater availability and, consequently, on ecosystem health (named freshwater ecosystem impact; FEI) as well as the effects of direct groundwater use, limiting freshwater accessibility on the long-term (freshwater depletion; FD). On the other, Pfister et al. (2009) considered an endpoint angle and defined a method based on the Eco-indicator-99 assessment methodology (Goedkoop and Spriensma 2001), where the potential damages of water consumption are evaluated for three areas of protection: human health, ecosystem quality, and resources.

Even when those approaches are quite young, there are already some references available on their application (Milà i Canals et al. 2010; Muñoz et al. 2010; Ridoutt and Pfister 2010; Pfister et al. 2011; Núñez et al. 2012). Still, the general trend in LCA studies has been to ignore the assessment of the impact of freshwater use or, in the best case, its inclusion on the LCI level (Milà i Canals et al. 2006; Muñoz et al. 2006; Hospido et al. 2009).

Both Milà i Canals et al. (2009) and Pfister et al. (2009) compile inventory water flows of the product system applying the virtual water (Allan 1998) and water footprint concepts (Hoekstra et al. 2010), with focus on the consumption or evaporative use of blue water (i.e., withdrawal of surface and groundwater).

On the LCIA level, the recent developments allow the discrimination between regions with different water scarcity (e.g., Milà i Canals et al. 2010), but they still lack on the inclusion of other artificial water resources (the term artificial has been defined here as opposite to conventional natural resources (i.e., surface and ground water)), such as regenerated water from wastewater treatment plants or desalinated water from sea or brackish water, when assessing the impact associated to freshwater use. Those water flows are gaining importance in arid and semi-arid countries, such as Spain, that suffer from water scarcity but are wealthy enough to overcome water deprivation by technology development.

Agriculture is the most water-demanding activity worldwide, accounting for about 70 % of the whole water withdrawn (FAO 2010), and therefore water consumption and its related impacts should be included in LCA studies of food products or biofuels, in order to assist to identify more sustainable paths of performance. This paper presents a procedure to incorporate water source information at the inventory level and evaluate, by means of a case study that tests different scenarios of water availability, the influence of that profile on the environmental impact assessment level. The approach is expected to help users to better address water consumption in LCA studies that includes agricultural irrigated products.

## 2 Methods

### 2.1 Structure of the proposed method

The methodology here presented lies on two main elements: the *irrigation mix* concept and the FEI indicator defined by Milà i Canals et al. (2009).

When sourcing water for irrigated crops, several options can be available depending on the geographical conditions as well as the economic and technological level of development. Using the river basin as the reference area, we identified the following origins at the LCI level:

- Surface water (SW): Water that is extracted from the natural surface sources of the basin
- Ground water (GW): Water that is extracted from groundwater bodies of the basin through wells
- Runoff water (RW): Water requirement that is covered by agricultural runoff reclamation of the basin and reused again
- Desalinated water (DW): Water that is desalinated in the basin and used for irrigation
- Wastewater (WW): Regenerated wastewater in the basin that is reused
- Transferred water (TW): Water from natural sources in other basin that is transferred from being used in the basin under study

The first five can be included under the term internal origins (i.e., the sources available within the basin boundaries), while the last one is an external one (or related to

sources that are transferred from outside the basin). The identification of these sources follows the framework described by Steward and Weidema (2005), which is based on the concept of resource functionality. All these sources build up what we have named the irrigation mix/profile, similar to the electricity production mix that characterizes the background information associated to the electricity used by a product, a process, or a service.

This distribution of freshwater sources was also considered in the impact assessment stage, following the FEI indicator (Milà i Canals et al. 2009), stated as volume of ecosystem-equivalent water per volume of irrigated water and calculated from Eq. (1), which refers to the volume of water likely to affect freshwater ecosystems:

$$\mathrm{FEI} = \mathrm{IW}\ \mathrm{CF} \tag{1}$$

Where IW is the amount of irrigated water consumed and CF is the characterization factor, calculated as follows:

$$\mathrm{CF} = \sum\nolimits_i (x_i\ \mathrm{CF}_i) \tag{2}$$

Being $x_i$ the fraction of the total irrigated water used that is covered by each of the different origins above identified ($x_i$=IW$_i$ / IW) and CF$_i$ the individual characterization factor associated to each water source.

For the natural sources of water (i.e., surface water, ground water, and transferred water), the definition of CF$_i$ is based on the withdrawal-to-availability ratio already used by several authors (Berger and Finkbeiner 2010). This ratio relates the total annual freshwater extraction for human uses in a specific region (i.e., water use, WU) and the annually available renewable water supply in that region (i.e., water resources, WR). In particular, the water stress indicator (WSI) as defined by Milà i Canals et al. (2009) has been employed here (Eq. (3)), as unlike other water scarcity indexes it also takes into account the environmental water requirements (EWR) of the river basin:

$$\begin{array}{l}\mathrm{CF}_{i,j} = \mathrm{WSI}_j = \mathrm{WU}_j / \left(\mathrm{WR}_j - \mathrm{EWR}_j\right) \\ \text{for } i = \mathrm{SW},\ \mathrm{GW},\ \text{and TW};\ j = \text{river basin}\end{array} \tag{3}$$

For the CF$_{SW}$ and CF$_{GW}$, it is important to mention that the term WR (Eq. (3)) for the basin under study considers not only the natural resources available in the basin (surface and ground water) but also the additional supplies achieved by reusing naturally available existing freshwater resources (wastewater and agricultural runoff reclamation) as well as the new ones obtained with seawater desalination. However, note that for the CF$_{SW}$ and CF$_{GW}$, the transferred water from other basin (TW) is not included within WR, as doing it would reduce the water stress in the receiving basin and therefore wrongly show the interbasin transfers as a partial solution, regardless of the environmental consequences on the origin river basin. So, for example, reduced river discharge in the providing basin could lead to freshwater fish species losses (Hanafiah et al. 2011) and to a higher concentration of nutrients and pollutants (Xenopoulos and Lodge 2006). Besides, and although the term EWR (Eq. (3)) is based on river flow variability, there are complex physical interactions between river and ground water flows (Sophocleous 2002) that led us to take also into account the freshwater ecosystem needs in the definition of the CF$_{GW}$, and therefore, as a rule of thumb, the same CF has been considered for both sources (SW and GW).

Concerning to the term WR included in CF$_{TW}$, only natural resources have been considered as the water to be transferred is directly extracted from surface water bodies, so the additional sources likely to be available in that basin do not play any role here.

For the artificial water sources, CF$_i$ has been stated as 0 due to the following reasons:

- Agricultural runoff water: To avoid double counting, the stream coming from exceeding irrigation does not contribute to the freshwater impact indicator as its associated impact was already calculated when extracted from natural sources for the first time.
- Desalinated water: In agreement with Muñoz et al. (2010), seawater is considered an unlimited resource and does not contribute to any impact related to water consumption, but it can play an important role in other impact categories, such as global warming, due to the high energy requirements of the desalination processes.
- Wastewater: As stated by Muñoz et al. (2010), water reuse has a beneficial rather than a detrimental effect as it decreases the pressure on freshwater ecosystem.

### 2.2 Exemplifying the model: calculation of CFs for a selected watershed

The procedure that should be followed to derive water source-dependent CFs is shown in this section for a Spanish water basin. Spain is the most arid country within the European Union, so water management is an important and controversial issue. The country is characterized by a not uniform distribution of fresh water availability and water resource demands (Alcamo et al. 2003; Downward and Taylor 2007). It is divided in 22 main river basins (Fig. 1), with different levels of water scarcity from North to South and depending if they are Atlantic basins or Mediterranean ones.

The proposed method was applied to the Segura basin, selected for its water deficiency (water stress index=1, according to Pfister et al. 2009), for its importance on the agricultural Spanish sector, both in terms of production (MARM 2010a) and water demand (Fig. 2), as well as for

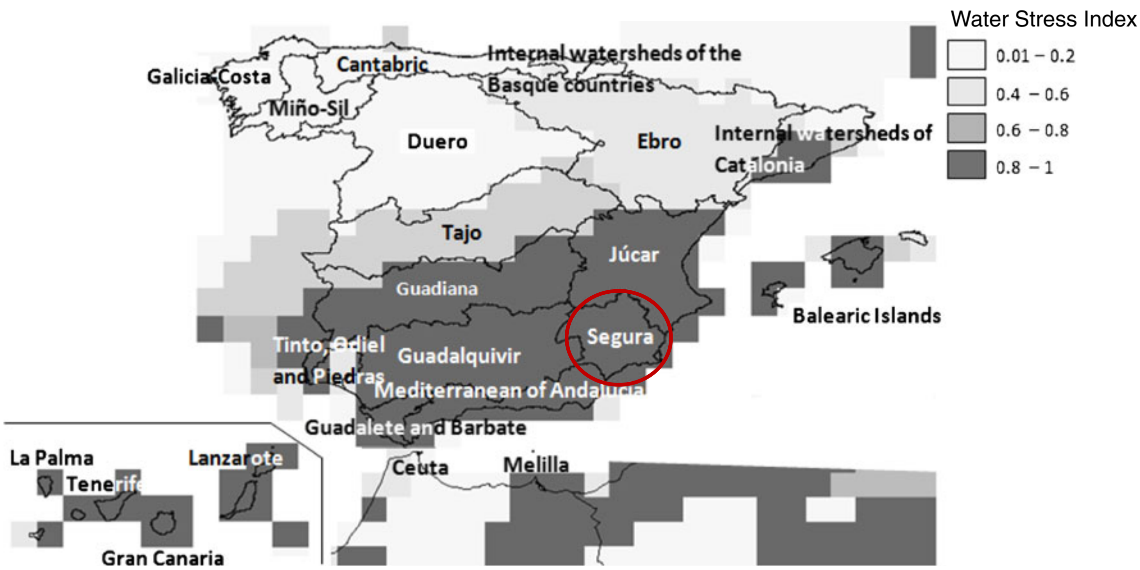


**Fig. 1** Main basins in Spain and their level of water scarcity, stated as the water stress index ≤1 according to Pfister et al. (2009)

being the second basin in terms of wastewater reuse for irrigation in Spain (Fig. 3).

In fact, the Segura basin is one of the basins affected by the A.G.U.A. program (MARM 2010d), a plan that is based on increasing desalination capacity as well as regeneration of wastewater in order to complement the natural water resources and augment the available freshwater in the Mediterranean basins (see Muñoz et al. (2010) for a comparative LCA study on this program and its predecessor, the Ebro river water transfer).

### 2.3 An additional environmental indicator

LCA methodology is able to quantify the environmental impact of a product, process, or service from a holistic perspective, avoiding so the transfer of pollutants between compartments and between impact categories. Being aware that, on a global scale, water is not a limited resource and that through technology it can be available almost everywhere, we suggest complementing the model for the estimation of impact on freshwater resources (by means of the FEI indicator) with another environmental impact category that provides us the probable side effects related to the consumption of the different water sources identified. To do so, the use of energy associated to the different water sources available in the Segura basin was quantified (Table 1) and evaluated in terms of global warming potential (GWP) (IPCC 2007) by using the corresponding emission factor for the Spanish electricity profile (0.508 kg $CO_2$-eq/kWh, according to the Ecoinvent process: Electricity, low voltage at grid/ ES, including national production and

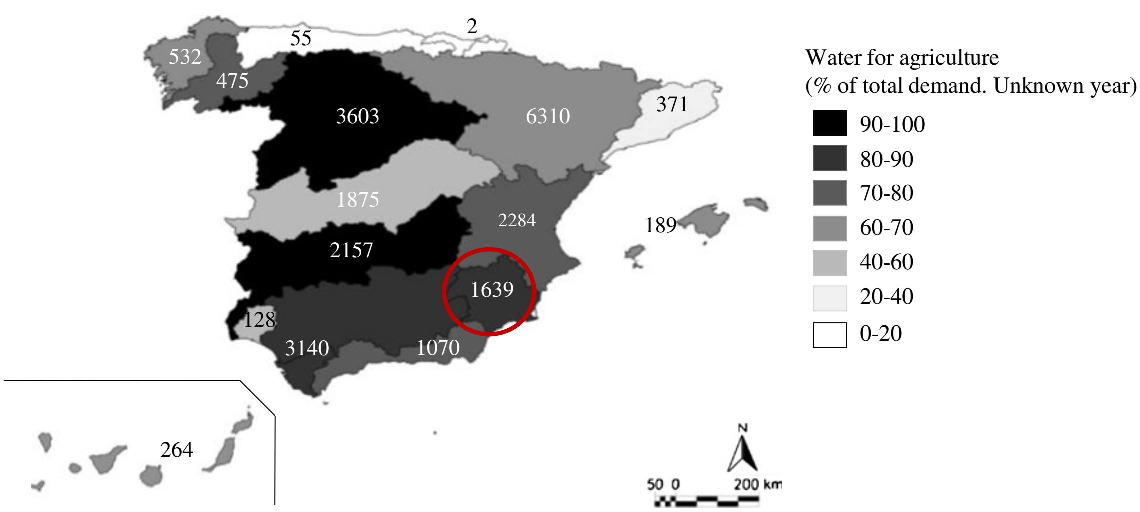


**Fig. 2** Water used in agriculture per water basin (MARM 2010b), both in absolute ($10^6 m^3$/year) and relative (%) terms


**Fig. 3** Volume of regenerated wastewater per water basin (data for 2007) (MARM 2010c), both in absolute ($10^6 m^3$/year) and relative (%) terms

import/export (data from 2008), transformation from high–medium and medium–low voltage, direct $SF_6$ emissions to air, and electricity losses from transmission systems) and the impact assessment method IPCC 2007 GWP 100y v1.02, included in the LCA software SimaPro.

## 3 Results

### 3.1 CF calculation: the case of the Segura watershed

Table 2 presents the irrigation mix (the first term in Eq. (2)) of the Segura basin, i.e., the different water flows there used for irrigation, which comprises the six sources (five internal and one external) identified in Section 2.1. Almost 90 % of the water use in the Segura basin is required for agricultural purposes (MARM 2010b). Therefore, and taking into account the data gathered (see Table 2), the current scenario is characterized by an incomplete coverage of the irrigation demand of the basin: 1,639 $10^6 m^3$/year demanded (MARM 2010b) versus 1,501 $10^6 m^3$/year available (data from Table 2). Besides, the present situation is depicted by a total dominance of the natural water resources (SW, GW, and TW), being the artificial sources (RW, DW, and WW) accountable for 11 % of the water used for irrigation in the basin, leaving room for improvements.

Table 2 also displays the individual characterization factors (the second term in Eq. (2)) that allows the integration of the different sources of water into the same impact indicator. As expected, the values for the $CF_{SW}$ and $CF_{GW}$ are lower (1.445) when including the artificial water resources from wastewater recovery, excess water irrigation reclamation, and seawater desalination within the available water resources in the watershed, instead of considering only the natural ones (1.816 if calculated as defined by Milà i Canals et al. (2009)).

Once the irrigation profile ($x_i$) and the individual characterization factors ($CF_i$) are calculated, the final CF of the water basin (Eq. (2)) can be obtained: 1.195 $m^3$ ecosystem-equivalent water/$m^3$ water. The figure is significantly lower than the value obtained if the mix is ignored and the WSI of the Segura basin is directly applied: 1.445 $m^3$ ecosystem-equivalent water/$m^3$ water. The comparison of both values clearly reflects the benefits associated to the use of artificial water sources and provides a quantification of the improvement achieved on the water stress of the Segura basin.

**Table 1** Energy use per cubic meter of water from different origins at the Segura basin

| Type | $kWh/m^3$ | Comments |
|---|---|---|
| SW | 0.14 | Average energy use for supply water in Spanish irrigated areas (Muñoz et al. 2010) |
| GW | 0.90 | Typical energy use for groundwater extraction in southeastern Spain (Muñoz et al. 2010) |
| RW | 0.00 | No energy demand has been allocated to this flow, assuming that exceeding water reaches the irrigation ditch by gravity and is then available for further use downstream |
| DW | 2.64 | Average value of the optimistic and pessimistic conditions (Muñoz et al. 2010), taking into account that 57 % of DW comes from seawater and the remaining 43 % comes from brackish water (CHS 2010a) |
| WW | 1.31 | Average value of the optimistic and pessimistic conditions, including the energy required for the advanced treatment and the water distribution from treatment plants (Muñoz et al. 2010) |
| TW | 2.75 | Average value of the optimistic and pessimistic conditions (Muñoz et al. 2010) |

### 3.2 Environmental impacts of water consumption in the Segura watershed

Once the CF of the Segura basin is obtained, Eq. (1) calculates the FEI indicator. So, taking as reference flow 1 $m^3$ of water for irrigation in the Segura basin, the environmental impact of freshwater consumption can be estimated: 1.195 $m^3$

**Table 2** Irrigation profile and characterization factors for the different water sources available in the Segura basin

| | $IW_i$ ($10^6 m^3$/year)[a] | $x_i$ | $CF_i$ |
|---|---|---|---|
| Surface Water (SW)[b] | 860 (CHS 2010b) | 0.57 | 1.445[c] |
| Ground Water (GW)[b] | 210 (CHS 2010b) | 0.14 | 1.445[c] |
| Runoff Water (RW) | 45 (CHS 2010c) | 0.03 | 0 |
| Desalinated Water (DW) | 53 (CHS 2010a)[d] | 0.04 | 0 |
| Wastewater (WW) | 65 (MARM 2010e) | 0.04 | 0 |
| Transferred Water (TW)[e] | 268 (CHS 2010d) | 0.18 | 0.923 (Milà i Canals et al. 2009) |
| Total | 1,501 | 1.00 | 1.195 |

[a] See the supplementary information (text S1) for details on data collection and calculations

[b] Assuming that the total own resources available are designated to irrigation

[c] See the supplementary information (text S2) for details on data collection and calculations

[d] Information provided through the online contact form www.valdelentisco.es/contactav.asp

[e] From the Tagus basin to the Segura basin

ecosystem-equivalent water/$m^3$ irrigation water. Besides, the irrigation mix also gives a better picture of the real contribution of irrigation to other impact categories (here, exemplify by the GWP): 0.433 kg $CO_2$-equivalent/$m^3$ irrigation water, being more than half of the impact due to transferred water (Fig. 4), followed by groundwater and desalinated water with a contribution of 15 and 11 %, respectively. Surface water, by far the most significant provider of irrigation water (57 %) as well as of freshwater impacts (69 % of the total FEI), only represents 10 % of the impact in terms of global warming. In fact, if the irrigation mix is ignored and this indicator is evaluated simply by means of 1 $m^3$ of irrigation water from surface water, the value obtained would be 0.076 kg $CO_2$-equivalent/$m^3$ irrigation water, more than five times lower than the value here calculated.

### 3.3 Application of the method to an irrigated crop grown in the Segura watershed

According to the objective of this paper, the model presented should help LCA practitioners to better address water use in LCA studies that includes agricultural irrigated products. An LCA study on lettuce production in the Segura

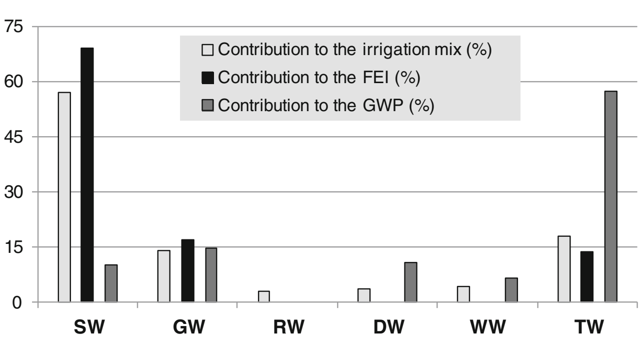


**Fig. 4** Irrigation mix at the Segura basin and its share in the FEI and the GWP indicators

basin (Hospido et al. 2009) was selected for the application of the irrigation profile here developed to move from the inventory level to the impact assessment level. Growing 1 kg of lettuce in this water basin requires 66.80±33.12 l of water (from farm to a UK Regional Distribution Centre), being 90 % of that figure (60.29±32.85 l) irrigated water consumed at the farm (Hospido et al. 2009). Following the values of CF previously calculated, the impact of water consumption would vary depending on the water source:

1. Use of the irrigation mix as default value when no information of the particular water sources consumed by the inventoried farms is available (CF=1.195 $m^3$ ecosystem-equivalent water/$m^3$ water). According to Eq. (1), FEI=1.195×60.29=72.05 $m^3$ ecosystem-equivalent water/tonne lettuce.
2. Use of the corresponding CF if information of the specific water source consumed for irrigation is available. For example, Hospido et al. (2009) specified that groundwater is used for irrigation by the inventoried farms. Accordingly, the $CF_{GW}$ has to be used (1.445 $m^3$ ecosystem-equivalent water/$m^3$ water) and the FEI would turn to be equal to 87.12 $m^3$ ecosystem-equivalent water/tonne lettuce.

The second alternative better represents the real irrigation water sources consumed within the farms. This approach is likely to be feasible for individual assessments, but when a more general overview is required, the default irrigation mix CF for the basin here introduced can be of great interest, as it provides a more realistic picture of the water sourcing at the basin level.

### 3.4 Scenario analysis of different irrigation profiles in the Segura watershed

As mentioned above, the irrigation requirements at the Segura basin are not totally satisfied, being its deficit around

8.5 % (note that this value corresponds to the best estimation situation, where all the natural resources (SW and GW) available in the basin are allocated to agricultural purposes).

With the hypothesis that all the irrigation demand should be covered, several alternatives were defined (see Table S1 in the Electronic supplementary material for further details) and assessed on the basis of two environmental indicators selected (FEI and GWP, Fig. 5):

- Scenario 0 is the baseline scenario, the current situation that is considered as reference for the evaluation of the alternatives proposed.
- Scenario 1 makes use of all the regenerated wastewater available in the basin and covers the remaining irrigation water with extra desalinated water.
- Scenario 2 employs all the desalinated water available in the basin and covers the remaining irrigation water with extra regenerated wastewater.
- Scenario 3 considers the maximum potentials, defined on the basis of the built facilities in the basin, of both regenerated and desalinated water available in the basin. By doing so, there is an excess of water available for irrigation and therefore the amount of natural water that is allocated to this use can be reduced.
- Scenario 4 makes also use of the maximum potentials of both DW and WW and goes a bit further by assuming that enough water to remove the transfer from the Tagus river can be achieved from those two sources (50 % DW–50 % WW).
- Scenario 5 is built on the previous one but considering that the hypothetical extra additional water is only provided through wastewater reclamation.

At first glance, the tendency is clear: the FEI associated to the provision of 1 $m^3$ for irrigation in the Segura basin can be reduced at the expenses of higher energy use, and therefore higher GWP (scenarios 1, 2 and 3). This conclusion is not surprising, and it is in line with the adaptation capacity term (Boulay et al. 2010), where the Gross National Income was selected as the socioeconomic parameter that measures the level of adaptation to changes in water availability. So, low-income countries will have low adaptation capacity and therefore will suffer from water deprivation while high-income countries, such as Spain, will use their artificial sources (desalinated water or regenerated wastewater) to decrease their water stress.

However, this tendency is not followed by the final scenarios (4 and 5) where a hypothetical situation has been defined: the suppression of the transfer from an external basin (TW) at expenses of the increase of the potential of local artificial sources (DW and WW). This proposal falls within the so-called A.G.U.A. Program, already evaluated from an LCA perspective (Muñoz et al. 2010), and the results obtained here are in line with those reported there.

Regardless of the alternative chosen, the FEI always decreases in comparison to the actual situation (scenario 0). The higher reduction (21 % less impact) is associated to the eradication of the Tagus transfer (scenarios 4 and 5) which supports the environmental rationale that traditionally has been claimed against the interbasin water transport (EeE 2010).

The same behavior does not exist regarding the second environmental indicator (GWP), with some of the options evaluated (scenarios 1–3) increasing the associated impact per cubic meter of water provided (maximum of 12 %) while the others (scenarios 4 and 5) reducing the related emissions of greenhouse gasses (maximum diminution 22 %). How to ponder those two indicators (and others that can be of interest) in a particular study is related to the subsequent phases of the LCIA stage (normalization, grouping, and weighting), which is beyond the scope of the present paper.

## 4 Discussion

Although this paper does not present a new impact assessment method for the freshwater use category, we profit from the structure defined by the International

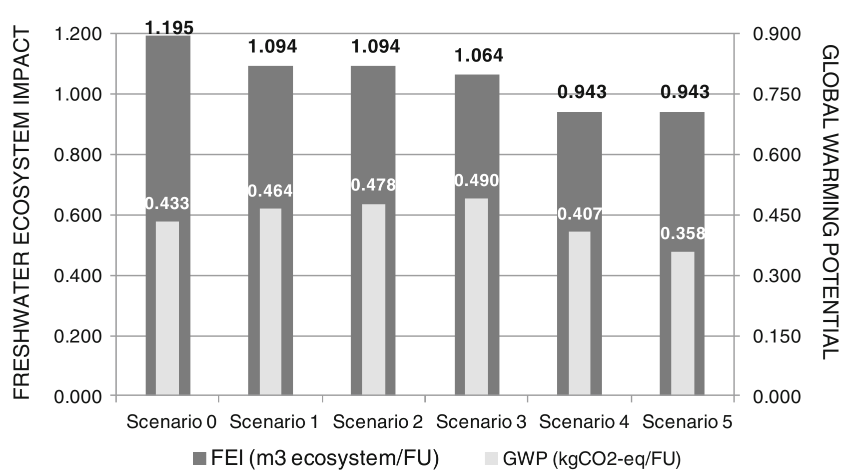


**Fig. 5** Environmental indicator results for the different alternatives proposed for providing 1 $m^3$ of water for irrigation in the Segura basin

Reference Life Cycle Data System (ILCD) handbook (JRC 2010) to evaluate the approach here described. The ILCD employs a set of criteria and sub-criteria specific to each impact category to analyze coherence of life cycle impact assessment methods. By applying this procedure, we aim at highlighting the main characteristics of our method in order to facilitate comparisons with other schemes addressing water use in LCA.

### 4.1 Completeness of scope

The method is an adjustment of the FEI indicator (Milà i Canals et al. 2009). The modification aims at taking into account the different natural and artificial origins of water resources, both at the LCI and the LCIA levels. The objective of the method is to show the uneven environmental relevance of consuming different sources of water. In this regard, the impact category indicator was defined at the midpoint level, close to the LCI, instead of at the endpoint level.

The model is globally applicable and spatially explicit, as it accounts for the unequal geographic distribution of water on Earth, by reporting demand and availability of water resources at the water basin level. This basin mix is adaptable to other spatial scales, as far as information can be accessed. Here, the method was applied to the Segura basin, which is quite small and uniform, but more detailed scales, such as the subbasin, would fit better for larger basins. Also, the model can be easily adapted to temporal changes on the irrigation profile of a water basin, when, for example, more artificial water from new desalination plants will be available.

The method was developed to assess impacts of freshwater use associated to the most water-demanding activity in the world, agriculture, in a given water basin. However, completeness of freshwater ecosystem impacts per water basin can be easily reached with the aggregation of all water uses.

### 4.2 Environmental relevance

The method adequately distinguishes among natural (surface and groundwater) and artificial (different backup technologies) origins of irrigation water, so green water is discounted. However, and as described in Section 2.1, some simplifications can be required as it was the case in the Segura basin, where the best approximation found was to allocate the same CFs to SW and GW.

Only freshwater consumptive use—water evaporated and product integrated—is considered. Degradative uses—water quality alteration—are disregarded, so double counting of impacts already accounted for in other LCA impact categories is avoided. For example, nutrient water pollution is evaluated in the eutrophication impact category and toxicity of pesticides in the human toxicity and ecotoxicity impact categories.

Some can argue that the approach is biased by the definition of the water stress indicator used (Eq. (3)), as the impact reduction is not calculated against only natural water but through the increase of artificial water sources (e.g., wastewater, desalination). However, we think that giving value to the fact of recovering water functionality for irrigation purposes (and therefore increasing water sources) is not a way of biasing the results.

In addition, the WSI is a good meter of the water resources available for human uses after subtracting, in every river basin of the world, the necessary water for the maintenance of freshwater-dependent ecosystems (EWR), which depends on some hydrological components of the river flow, so FEI varies with location.

### 4.3 Scientific robustness and certainty

The cause–effect chain which leads from the environmental intervention, i.e., the consumptive water used in irrigation, to the environmental impacts on ecosystems is only partly modeled up to the midpoint level, with an indicator of the ecosystem-equivalent volume of water. The link of this midpoint with an endpoint indicator expressing the ultimate damages on species (e.g., potentially disappeared fraction of species) is not addressed, given that more research of the effects of water scarcity on ecosystems is needed. Nevertheless, the flexibility of the model allows for the cause–effect chain to be completed when more knowledge of this relationship is available.

The temporal and spatial specifications of the model are highly flexible, both for the irrigation mix of the LCI as well as for the WSI of the LCIA; this means that the model can be improved regarding geographical and temporal differentiation. While in the current research, we compared water use and availability on an annual basis, the WSI can also be calculated on a monthly step to incorporate the variability of the water flow throughout the year. The conservative approach of assuming a standard monthly environmental flow requirement (EWR) of 20 % of the total runoff (Richter et al. 2012) can be adopted if water basin specific studies have not been yet performed.

The most important source of uncertainty of the indicator comes from the input data used to apply the model: different data sources for building the irrigation mix and the WSI provide information for different spatial and temporal spans. Therefore, comparative studies should be carefully handled and, when possible, uncertainty indicators (either quantitative or qualitative) should be reported.

The FEI indicator cannot be verified against monitoring data, as the volume of water ecosystem-equivalent is an impact index resulting from multiplying volumes by water scarcity factors.

4.4 Documentation, transparency, and reproducibility

WU and WR data necessary for deriving characterization factors is accessible for natural resources (surface and groundwater) of all the water basins of the world (Alcamo et al. 2003). However, in many watersheds, documentation of the EWR and artificial WR is lacking. This can hamper the use of the proposed method in LCA studies. To overcome this situation, third parties are encouraged to measure and report basin local data. In this sense, the requirements of the Water Framework Directive (EC 2000) are expected to supply enough data in all river basin districts across the European Union.

4.5 Applicability

The case study on lettuce production in the Segura basin included in the paper showed the feasibility of the method proposed in capturing ecosystem impacts due to the consumption of different water origins. As shown with the case study, the application of the methodology demands significant amount of detailed information. On water basins less well documented than the Segura basin, problems may appear when applying the method. In cases like that, the practitioner will have to take decisions and establish assumptions that allow the method to be useful at the expense of higher uncertain results. For instance, in our case study and concerning to the runoff water flow, the Segura Basin Administration states that "the reuse of irrigation returns […] by means of open-channel drainage and irrigation channels has a current volume of reuse of approximately 45 million m3/year" (CHS 2010c). We can then assume that this flow corresponds to the amount of RW available after evaporative losses (which have been reported between 7 and 14 %, according to Emmenegger et al. 2011). Making these kind of decisions is mostly unavoidable in LCA studies, as statistics are usually incomplete or information is vaguely registered.

The collection of the required data for the provision of characterization factors for worldwide watersheds was considered to be out of the scope of this paper. What is true is that the procedure described here can be applicable elsewhere, so we recommend carrying out more studies that apply the outlined method in order to check the transferability of the approach to other river basins.

## 5 Conclusions

The inclusion of the water mix in the irrigation profile of the LCI as well as in the water stress index of the LCIA, as being described in this paper, results in a more realistic assessment of the impacts of freshwater use associated to crops. The approach makes visible the benefits of promoting the use of alternative water resources, as lower CFs are assigned to scenarios with higher alternative resource utilization. However, when other environmental indicators apart from water consumption are taken into account—the contribution to climate change in this study—, the transference of ecological burdens between impact categories has been revealed: freshwater ecosystem impacts can be reduced in some scenarios at the expenses of higher energy consumption, therefore greater contribution to climate change. These outcomes highlight the importance of a comprehensive assessment with multiple environmental indicators when system alternatives are being compared using a life cycle perspective.

The implementation of the irrigation mix concept on a case study (the Segura basin) allowed the quantification of promoting alternative water sources in a region suffering from significant water stress as well as to improve knowledge on the environmental impact associated to freshwater consumed by one of the irrigated crops (lettuce) grown there.

We recommend using the approach defined here in order to check its applicability to other river basins as well as to other products; by doing so, both us and other LCA users will benefit from the methodological improvements of this environmental management tool.

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